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Enhancement of heat transfer using nanofluids—An overview

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ABSTRACT

A colloidal mixture of nano-sized particles in a base fluid, called nanofluids, tremendously enhances the heat transfer characteristics of the original fluid, and is ideally suited for practical applications due to its marvelous characteristics. This article addresses the unique features of nanofluids, such as enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion, thermophoresis, etc. In addition, the article summarizes the recent research in experimental and theoretical studies on forced and free convective heat transfer in nanofluids, their thermo-physical properties and their applications, and identifies the challenges and opportunities for future research.

Contents

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Nomenclature

A	cross-sectional area (m^2)
C_p	specific heat (J/kg K)
D	tube diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
m	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
q''	heat flux (W/m^2)
Re	Reynolds number
T	temperature (°C)

Greek symbols

β	thermal dispersion coefficient (N/m^2 K)
φ	volume fraction
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
γ	particle size (nm)

Subscript

f	bulk fluid
nf	nanofluid
w	tube wall
x	axial distance
bf	base fluid
i	inner wall
o	outer wall

Abbreviation

CHF	critical heat flux
CNT	carbon nano tube
HTC	heat transfer coefficient

1. Introduction

Ever since the adverse effect of green house gases was discovered, leading to the Kyoto Protocol [1], the search for methods and technological advancement to mitigate the impact of global warming on Planet Earth became a pressing need for the research and industrial communities. The Protocol had exhorted both the developed and developing countries to show intense curiosity with a sense of participation, to find definitive ways to tackle the issue. Subsequent meetings which were held in many countries had called for a gentle decline in the production of green house gases. Even as scientists subscribed to a number of methods to tackle the carbon footprints, the global energy need and inefficient thermal-fluid systems always increased the green house gases.

A reduction in energy consumption is possible by enhancing the performance of heat exchange systems. Heat transfer is one of the most important processes in industrial and consumer products and it is worth addressing its influence over carbon footprints. For instance, the present telecommunication demand for enhanced functionality in circuit boards, results in high process density circuit boards. In such cases, the company spends more than 50% of the total electricity on the thermal management of electronic cooling systems [2]. Further, one of the most influential regulations is the 65 Dba noise limit in a central office environment compared to the 85 Dba in data centers and thus, typical air-cooling methods are unsuitable for these conditions [3]. The dozens of methods such as Fin-Foam Heat Sink, Minichannels, Microchannels, Novel interface materials, Dielectric mist cooling, Forced convective boiling, etc. and their combinations are limited to heat removal of up to 1000 W/cm^2. Some of the electronic systems like ultra-high heat flux optical devices, high-powered X-rays and lasers demand as high as 2000 W/cm^2 of heat removal [4]. Similarly, the growth of Heating Ventilation and Air-Conditioning (HVAC) and chemical processing equipment had adversely increased the carbon footprints. The paradigm shift in their design with respect to heat transfer will both simultaneously reduce the size of the heat exchangers and the energy consumption. In many industrial applications, the conventional heat transfer fluids are refrigerants, water, engine oil, ethylene glycol, etc. Even though an improvement in energy efficiency is possible from the topological and configuration points of view, much more is needed from the perspective of the heat transfer fluid. Further, enhancement in heat transfer is always in demand, as the operational speed of these devices depends on the cooling rate. New technology and advanced fluids with greater potential to improve the flow and thermal characteristics are two options to enhance the heat transfer rate and the present article deals with the latter option. One such latest advancement in heat transfer fluids, is an engineered colloidal mixture of the base fluids and nano-sized metallic particles (1–100 nm). The earlier versions of colloidal fluids such as micro-fluid substances tend to sediment and cause erosion in the moving component. However, nanofluids are claimed to be a non-agglomerated mono-dispersed particles in the base fluids, which proved to be enhancing the heat transfer more than 50% in real-time applications even when the volume ratio of the nanoparticle to base fluid is less than 0.3% [5]. As the need for more efficient heat transfer systems increases, researchers have introduced various heat transfer enhancement techniques since the middle of the 1950s. The exponential increase in the number of research articles dedicated to this subject thus far shows a noticeable growth and the importance of heat transfer enhancement technology. Some recent review articles [6–10] have covered a variety of methods for the enhancement of heat transfer. Investigation in convective heat transfer characteristics has been carried out in recent times. In this paper, the various articles related to the mechanism of nanofluid heat transfer, thermo-physical properties and pioneering experiments related to convective and boiling heat transfer of nanofluids are discussed. This article presents the recent research in natural, forced and two-phase convective heat transfer in nanofluids and its applications, and identifies the challenges and opportunities for future research.

2. Nanofluids

Enhancement of convective heat transfer and thermal conductivity of liquids was earlier made possible by mixing micron-sized particles with a base fluid (Maxwell paper) [11]. However, rapid sedimentation, erosion, clogging and high-pressure drop caused by these particles has kept the technology far from practical

use. A very small amount of nanoparticles, when dispersed uniformly and suspended stably in base fluids, can provide impressive improvements in the thermal properties of base fluids. Nanofluids, which are a colloidal mixture of nanoparticles (1–100 nm) and a base liquid (nanoparticle fluid suspensions) is the term first coined by Choi in the year 1995 [12] at the Argonne National Laboratory to describe the new class of nanotechnology based heat transfer fluids that exhibit thermal properties superior to those of their base fluids or conventional particle fluid suspensions.

The phases in the colloid are distinguishable and interact through weak surface molecular forces, preferably without any chemical reaction. Compared to micron-sized particles, nanoparticles are engineered to have larger relative surface areas, less particle momentum, high mobility, better suspension stability than micron-sized particles and importantly increase the thermal conductivity of the mixture. This makes the nanofluids a promising working medium as coolants, lubricants, hydraulic fluids and metal cutting fluids. Further, a negligible pressure drop and mechanical abrasion makes researchers subscribe to nanofluids for the development of the next generation miniaturized heat exchangers.

Based on their application, nanoparticles have been made of various materials [13–27] such as oxide ceramics, nitride ceramics, carbide ceramics, metals, semiconductors, carbon nanotubes and composite materials such as alloyed nanoparticles Al70Cu30 or nanoparticle core–polymer shell composites. In addition to nonmetallic, metallic, and other materials for nanoparticles, completely new materials and structures have been used, such as materials "doped" with molecules in their solid–liquid. The goal of nanofluids is to achieve the best possible thermal properties at the least possible volume fraction ($\varphi < 1\%$) in the base fluids. Thus, the suspension of nearly non-agglomerated or mono-dispersed nanoparticles in liquids is the key to significant enhancement in the heat transfer. In addition, Xuan and Li [28] suggested ultrasonic vibration of nanofluids and addition of surfactants to enhance the suspension.

3. Enhancement of thermal conductivity

A substantial increase in liquid thermal conductivity, liquid viscosity, and heat transfer coefficient, are the unique features of nanofluids. It is well known that at room temperature, metals in solid phase have higher thermal conductivities than those of fluids [29]. For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil. The thermal conductivity of metallic liquids is much greater than that of nonmetallic liquids. Thus, fluids containing suspended metal particles are expected to manifest enhanced thermal conductivities relative to pure fluids [30]. Masuda et al. [31] dispersed oxide nanoparticles (γ-Al_2O_3 and TiO_2 with $\varphi = 4.3\%$) particles in liquid and showed the increase in the thermal conductivity to be 32 and 11%, respectively. Grimm [32] dispersed aluminum particles ($\gamma = 80$–$1\ \mu m$) into a fluid and claimed a 100% increase in the thermal conductivity of the fluid for $\varphi = 0.5$–10%. Choi and Eastman [33] showed that the thermal conductivity of Cu–water and CNT–water nanofluids was higher compared to that of their base liquids. Eastmann et al. [34] showed that Cu–ethylene glycol (nanoparticles coated with thioglycolic acid) with $\varphi = 0.3\%$ gave a 40% increase in thermal conductivity. Recently, an attempt at the Indira Gandhi Centre for Atomic Research (IGCAR) was made, to align magnetic nanoparticles (Fe_3O_4 coated with Oelic acid) in a base fluid (hexadecane) in a linear chain using a magnetic field, which was applied to increase the thermal conductivity by 300% [35]. Further, it was proved that the thermal properties are tunable for magnetically polarizable nanofluids that consist of a colloidal suspension of magnetite nanoparticles. Moreover, the effective thermal conductivity depends also on other mechanisms of particle motion; the commonly explained physics are as follows.

3.1. Dispersion of the suspended particles

Dispersion is a system in which particles are dispersed in a continuous phase of a different composition. Surface-active substances (surfactants) can increase the kinetic stability of emulsions greatly so that, once formed, the emulsion does not change significantly over years of storage. Some of the surfactants are thiols [36], oleic acid [37,38], laurate salts, etc. Pak and Cho [39], Xuan and Li [28] and others claimed that the abnormal increase in thermal conductivity is due to uniform dispersion of the nanoparticles.

3.2. Intensification of turbulence

Even though thermal conductivity (k_{th}) is a function of primary variables such as thermodynamic pressure and temperature, in a turbulent flow the effective thermal conductivity ($k_{th} + k_{turb}$) due to the effects of turbulent eddies is many times higher than the actual value of k_{th}. Similarly in nanofluids, such intensification is believed to be possible due to the addition of nanoparticles. Xuan and Li [28]. However, Buongiorno [40] has claimed that due to the particle size, the effects of both dispersion and turbulence are negligible and not sufficient to explain the enhancement of thermal conductivity in nanofluids.

3.3. Brownian motion

It is a seemingly random movement of particles suspended in a liquid or gas and the motion is due to collisions with base fluid molecules, which makes the particles undergo random-walk motion. Thus, the Brownian motion intensifies with an increase in temperature as per the kinetic theory of particles. Keblinski et al. [41] and Koo and Kleinstreuer [42] have suggested that the potential mechanism for enhancement of thermal conductivity is the transfer of energy due to the collision of higher temperature particles with lower ones. The effectiveness of the Brownian motion decreases with an increase in the bulk viscosity.

3.4. Thermophoresis

Thermophoresis or the Sorét effect is a phenomenon observed when a mixture of two or more types of motile particles (particles able to move) is subjected to the force of a temperature gradient. The phenomenon is most significant in a natural convection process, where the flow is driven by buoyancy and temperature. The particles travel in the direction of decreasing temperature and the process of heat transfer increases with a decrease in the bulk density.

3.5. Diffusiophoresis

Diffusiophoresis (also called as Osmo-phoresis) occurs when there is a migration of particles from a lower concentration zone to a higher concentration one. However, this is not a favorable condition since the nanofluids may lose their non-agglomeration characteristics. Thus, the resulting fluid will result in a discrete spread in the particle density. Buongiorno [40] has stressed that the Brownian motion, thermophoresis and diffusiophoresis are significant in the absence of turbulent eddies.

The thermal conductivity enhancement ratio is defined as the ratio of the thermal conductivity of the nanofluid to that of the base fluid and this ratio depends on the material, size and shape of the

particle, volume concentration and the operating temperature itself. The influence of type of material on thermal conductivity enhancement has no effect for relatively low thermal conductivity particles and positive enhancement with higher thermal conductivity particles. For instance, the enhancement of thermal conductivity using metal particles is higher that the metal oxide particles. However, it is difficult to create metal particle nanofluids without particles oxidizing during the production process. A major obstacle for metal-particle nanofluids is eliminating the oxidation process during production and later during usage. Particle coating is one technique that has received some attention to solve this problem.

The smaller in particle size higher will be the enhancement. Since the surface to volume ratio will be higher for small diameter particles which results in uniform distribution of particles gives and the best enhancement. The most commonly used geometric shape of the particles is spherical and cylindrical. The cylindrical particles show an increase in thermal conductivity enhancement due to a mesh formed by the elongated particles that conducts heat through the fluid. This indicates the elongated particles are superior to spherical for thermal conductivity. The thermal conductivity enhancement increases with increased particle volume concentration. Metal oxide particle volume concentrations below φ = 4–5% produces an enhancement level up to about 30% is typical and metal particles with less than $\varphi < 1.5\%$ gives an enhancement up to 40%. The thermal conductivity of nanoparticles is more temperature sensitive than that of the base fluid. Consequently, the thermal conductivity enhancement of nanofluids is also rather temperature sensitive and a strong dependence of nanofluid thermal conductivity is due to the random motion of nanoparticles.

The physics of the above explained mechanisms is important and to be considered while studying the enhancement of thermal conductivity and the convective heat transfer of nano-sized colloidal mixture; the mechanisms are studied experimentally and theoretically by researchers and the summary of these investigations, findings and suggestions are presented in the following sections.

4. Experimental investigation

Enhancement in heat transfer was tried earlier also, with the help of suspended micro-particles. Ahuja [43,44] conducted experiments on the enhancement of heat transport in the laminar flow of water with micro-sized polystyrene suspension. The results showed a significant enhancement in the Nusselt number and heat exchanger effectiveness compared to that of a single phase liquid. Hetsroni and Rozenblit [45] investigated the thermal interaction between liquid and solid mixtures consisting of water and polystyrene particles in a turbulent flow. Interestingly, polystyrene has very low thermal conductivity close to only 0.08 W/m K. Still, the turbulence intensification and particle rotation effect are to be reasoned for an enhancement of heat transfer. The penalty in pumping power, clogging, agglomeration, sedimentation and erosion are some of the adverse effects of micro-particles. However, this issue has been eliminated with the use of stable nano-sized particulate colloids, and this has paved the way for researchers to further investigate the enhancement of convective heat transfer.

4.1. Forced convection heat transfer experiments with nanofluids

4.1.1. Experiments with metal oxide nanoparticles

Nanoparticles made from metal oxides, metals, nanotubes and graphite are widely investigated in base fluids such as water, ethylene glycol, acetone, etc. Some of the important experiments in macro, mini channels, heat pipes, etc. commonly used in many industrial heat transfer applications are discussed in the following sections.

Lee and Choi [46] used a nanofluid as a coolant in a micro-channel heat exchanger and compared the enhanced cooling rates with those of conventional water-cooled and liquid-nitrogen cooled micro-channel. The intensification of turbulence or eddy, suppression of the boundary layer, dispersion of the suspended particles, besides the augmentation of thermal conductivity and the heat capacity of the fluid were suggested to be the possible reasons for heat transfer enhancement. Eastman et al. [47] conducted tests to assess the thermal performance of CuO–water with φ = 0.9% under turbulent flow conditions and the heat transfer coefficient was higher by 15% than that of pure water. Pak and Cho [39] presented an experimental investigation of the convective turbulent heat transfer characteristics of nanofluids (γAl_2O_3–water and TiO_2–water) with φ = 1–3%. The Nusselt number for the nanofluids increased with an increasing volume concentration and Reynolds number. Wen and Ding [48] assessed the convective heat transfer of nanofluids in the entrance region under laminar flow conditions. Aqueous based nanofluids containing γ-Al_2O_3 nanoparticles (γ = 27–56 nm; φ = 0.6–1.6%) with sodium dodecyl benzene sulfonate (SDBS) as the dispersant, were tested under a constant heat flux boundary condition. For nanofluids containing φ = 1.6%, the local heat transfer coefficient in the entrance region was found to be 41% higher than that of the base fluid at the same flow rate. It was observed that the enhancement is particularly significant in the entrance region, and decreases with axial distance. Particle migration was reasoned for the enhancement. Heris et al. [49] examined and proved the enhancement of in-tube laminar flow heat transfer of nanofluids (water–CuO and water–Al_2O_3) in a constant wall temperature boundary condition. Similarly, Esfahany et al. [50] presented an investigation of the laminar flow convective heat transfer of Al_2O_3–water under constant wall temperature with φ = 0.2–2.5% for Reynolds number varying between 700 and 2050. The Nusselt number for the nanofluid was found to be greater than that of the base fluid; and the heat transfer coefficient increased with an increase in particle concentration. The ratio of the measured heat transfer coefficients increases with the Peclet number as well as nanoparticle concentrations. Lai et al. [51] studied the flow behavior of nanofluids (Al_2O_3–DI water; γ = 20 nm) in a millimeter-sized stainless steel test tube, subjected to constant wall heat flux and a low Reynolds number ($Re < 270$). The maximum Nusselt number enhancement of the nanofluid of 8% at φ = 1% was recorded. Jung et al. [52] conducted convective heat transfer experiments for a nanofluid (Al_2O_3–water) in a rectangular micro-channel (50 μm $\times$ 50 μm) under laminar flow conditions. The convective heat transfer coefficient increased by more than 32% for φ = 1.8% in base fluids. The Nusselt number increased with an increasing Reynolds number in the laminar flow regime ($5 < Re < 300$) and a new convective heat transfer correlation for nanofluids in Microchannels was also proposed. Williams et al. [53] investigated the turbulent convective heat transfer behavior of alumina (Al_2O_3–water and ZrO_2–water). The convective heat transfer and pressure loss behavior of nanofluids under a fully developed turbulent flow, matched the correlations of a single-phase flow. Duangthongsuk and Wongwises [54] showed an enhancement of heat transfer at a lower concentration of TiO_2–water (φ = 0.2%) and claimed that the convective heat transfer coefficient also depends on the experimental measurement system and calibration. Jang and Choi [55] showed an enhancement of the convective heat transfer coefficient of nanofluids (Al_2O_3–water with φ = 0.3%) up to 8%. Duangthongsuk and Wongwises [56] reported an experimental study on the forced convective heat transfer under varied heat flux boundary conditions and pressure drop characteristics of a

nanofluid consisting of water and 0.2 vol.% TiO_2 nanoparticles of 21 nm diameter flowing in a horizontal double-tube counter flow heat exchanger under turbulent flow conditions. The results showed that the convective heat transfer coefficient of nanofluid is slightly higher than that of the base liquid by about 6–11%. The heat transfer coefficient of the nanofluid increases with an increase in the mass flow rate of the hot water and nanofluid. It was seen that the Gnielinski equation failed to predict the heat transfer coefficient of the nanofluid. Finally, it was also observed that the use of the oxide nanofluid has a little penalty in pressure drop.

4.1.2. Experiments with pure metal nanoparticles

Xuan and Li [57] experimentally studied the single phase heat transfer of the Cu–water nanofluid in tubes in the turbulent flow regime (Reynolds number between 10,000 and 25,000) with $\varphi = 0.3–2.0\%$ and proposed a heat transfer correlation. The convective heat transfer coefficient increased remarkably with the volume-fraction and with the flow velocity, with a negligible penalty in pumping power. Xuan and Li [58] measured the convective heat transfer of the Cu–water nanofluid in a small-hydraulic-diameter flat tube under laminar flow conditions. The Nusselt number of the nanofluid with $\varphi = 2\%$ increased by more than 39% compared with that of pure water. Zhou [59] investigated the enhancement of the single phase heat transfer of Cu–acetone particles with average particle sizes in the $\gamma = 80–100$ nm range and concentrations ranging from 0.0 to 4.0 g/l. Xuan et al. [60] investigated Cu–water (deionised) with $\gamma = 26$ nm and $\varphi = 0.5–2\%$. The Nusselt number increased proportionately with the Reynolds number, and for the same Reynolds number the ratio of Nusselt number of Cu–water to water varied from 1.06 to 1.39 when the volume fraction of copper nanoparticles increased from 0.5 to 2.0%.

Faulkner et al. [61] investigated the convective heat transfer of a CNT–water nanofluid in a micro-channel, with a hydraulic diameter of 355 μm, a Reynolds number between 2 and 17 and $\varphi = 1.1, 2.2$ and 4.4%. The results showed an enhanced heat transfer coefficient of CNT–water at highest concentration. Yang et al. [62] investigated the convective heat transfer of graphite nanoparticles dispersed in liquid in laminar flow in a horizontal tube heat exchanger, and reported that at 2 wt% the heat transfer coefficient of the nanofluids increased, compared with that of the base fluid; at 2.5 wt% the heat transfer coefficient 22 and 15% was higher than that of pure fluid at 50 and 70 °C respectively. Ding et al. [63] tested multi-walled carbon nanotubes (MCNT with $\varphi = 0.1–1.0\%$ with 0.5 wt% in aqueous solution) in a horizontal tube, and obtained a maximum enhancement of heat transfer (350%) at a Reynolds number of 800. Particle re-arrangement, shear induced thermal conduction, reduction of thermal boundary layer due to the presence of nanoparticles and high aspect ratio of CNTs were reasoned for the enhancement. Yulong et al. [64] experimentally analyzed forced convective heat transfer using aqueous and ethylene glycol-based spherical titania, and aqueous-based titanate nanotubes, carbon nanotubes and nano-diamond nanofluids. For aqueous-based titania, carbon and titanate nanotube nanofluids, the convective heat transfer coefficient enhancement exceeded, by a large margin. The competing effects of particle migration on the thermal boundary layer thickness and the effective thermal conductivity were suggested to be responsible for the heat transfer enhancement.

4.1.3. Inferences from forced convection heat transfer experimental studies

The observed results from the prior work done on the convective heat transfer performance of nanofluids clearly shows, that the suspended particles outstandingly increase the heat transfer performance of the base-fluid; and the nanofluids have higher heat transfer coefficients than those of the base-fluids at the same Reynolds number. High aspect ratio nanoparticles such as carbon nanotubes resulted in greater enhancement in thermal conductivity and the heat transfer coefficient, compared to spherical and low aspect ratio nanoparticles. It has been shown in many references that the heat transfer behavior of nanofluids and the application of nanofluids for heat transfer enhancement, are influenced by the effective thermo-physical properties of nanofluids and many other factors such as particle size, shape and distribution; Brownian motion, particle–fluid interaction and particle migration also have an important influence on the heat transfer performance of nanofluids. However, because of the lack of agreement between the experimental results reported by various groups, most of the studies lack physical explanation for their observed results. All the convective studies have been performed with oxide particles, Future convective studies must be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulence regions. Besides, the experimental data available for convective heat transfer are limited and insufficient to exactly predict the trend for heat transfer enhancement. Maiga et al. [65] reported that, with regard to the nanofluid thermal properties, the actual amount of experimental data available in the literature remains surprisingly small, and it is obvious that more works in this area will be published in the near future. Therefore, further research on the convective heat transfer of nanofluids is needed. Table 1 shows the summary of published experimental investigations of the convective heat transfer performance of various nanofluids.

4.2. Natural convection heat transfer experiments with nanofluids

Putra et al. [66] presented a study of the natural convection of nanofluids (Al_2O_3–water, CuO–water with $\varphi = 1–4\%$) using a horizontal cylinder test section with one end heated and the other cooled. The time to reach the steady state was much lesser even at relatively high particle concentrations, due to the non-agglomerative and mono-dispersive nature of the nanofluids. The heat transfer coefficient was found to be higher at the hot wall than at the cold wall. The natural convective heat transfer is higher for the CuO–water than the Al_2O_3–water nanofluid. Wen and Ding [67] conducted experiments on nanofluids (TiO_2–water with $\varphi = 0–1\%$) using two horizontally positioned aluminum discs separated by a 10 mm gap filled with nanofluid. The lower disc was heated at the bottom surface and the upper surface was open to the atmosphere. The temperature rose smoothly without any initial temperature oscillations as compared to micro-sized particles. The time to reach the steady state was also shorter and the heating surface temperature was found to increase with nanoparticle concentrations. The temperature difference between the walls increased with the volume fraction and reached 2.3 K for a $\varphi = 0.57\%$ compared to 1.5 K for pure liquid. Hwang et al. [68] theoretically presented the effects of the volume fraction, the size of nanofluids (Al_2O_3–water), and the average temperature of nanofluids on natural convective heat transfer characteristics in a rectangular cavity heated from the bottom. The results were validated with Touloukian et al. [69]. The results showed that as the volume fraction the of nanoparticles increased, the size of the nanoparticles decreased, the average temperature of nanofluids increased and the ratio of the heat transfer coefficient of nanofluids to that of base fluid decreased. Polidori et al. [70] investigated the natural convection heat transfer of Newtonian nanofluids in a laminar flow region with γ-Al_2O_3–water nanofluids whose Newtonian behavior was experimentally confirmed for $\varphi < 4\%$. The experimental investigations showed that the addition of nanoparticles deteriorated the heat transfer characteristics in the natural convective heat transfer region, whereas, the theoretical models predicted otherwise.

Table 1
Summary of experimental investigations in convective heat transfer of nanofluids.

Author	Base fluid	Particle material	Particle size	Volume fraction (vol.%)	Dimension	Flow regime, Re	Results and remarks
Pak and Cho. [39]	Water	$\gamma A1_2O_3$ TiO_2	13 nm 27 nm	1–3 1–3	ID: 1.066 cm Length: 480 cm S.S. tube	$Re = 10^4–10^5$ (turbulent flow)	Nu increased with increase in φ and Re
Eastman et al. [47]	Water	CuO	<100 nm	0.9	–	(Turbulent flow conditions)	HTC increased by >15% compared with pure water.
Wen and Ding [48]	Water	$\gamma A1_2O_3$	26–56 nm	0.6, 1, 1.6	ID: 4.5 mm Length: 970 mm Copper tube	Re = 500–2100 (laminar flow)	For $\varphi = 1.6\%$, the HTC is 41% higher than the base fluid
Heris et al. [49]	Water	$A1_2O_3$ CuO	20 nm 50–60 nm	0.2–3.0 0.2–3.0	ID: 6 mm Copper tube	Re = 650–2050 (laminar flow)	HTC was high when φ increases for $A1_2O_3$, Nu is high
Esfahany etal. [50]	Water	γAl_2O_3	20 nm	0.2, 0.5, 1, 1.5, 2, 2.5	ID: 6 mm Length: 1 m Copper tube	Re = 700–2050 (laminar flow)	HTC ratio increases with φ and 22% increase with Pe
Lai et al. [51]	Water	$A1_2O_3$	20 nm	0–1%	ID: 1 mm S.S. tube	Re < 270	Nu enhancement of 8% for $\varphi = 1\%$. $A1_2O_3$ nanofluid at Re = 270
Jung et al. [52]	Water	$A1_2O_3$	l0 nm	0.5–1.8%	Rectangular microchannel (50 μm × 50 μm)	5 < Re < 300	Conv. HTC increased by 32% for $\varphi = 1.8\%$. Nu increases with Re
Williams et al. [53]	Water	ZrO_2	46 nm 60 nm	0.9–3.6 0.2–0.9	OD: 1.27 cm Thick. = 1.65 mm S.S. tube	9000 < Re < 63,000 (turbulent flow)	Considerable heat transfer enhancement is observed
Xuan and Li [57]	Water	Cu	<100 nm	0.3, 0.5, 0.8, 1, 1.2, 1.5, 2	ID: 10 mm Length: 800 mm Brass tube	Re = 10,000–25,000 (turbulent flow)	Conv. HTC increases with increase in φ and flow velocity
Xuan and Li [58]	Water	Cu	26 nm	0.5, 1, 1.5, 2	Hydraulic diameter = 1.29 mm	Re = 200–2000 (Laminar flow)	Nu of nanofluid with $\varphi = 2\%$ is 39% more than pure water
Zhou [59]	Acetone	Cu	80–100 nm	0.0–4.0 g/1	ID: 16 mm Length: 200 mm Copper tube	–	Conv. HTC increases with addition of Cu nanoparticles
Xuan and Li [60]	Water	Cu	26 nm	0.5, 1, 1.5, 2	ID: 10 mm Length: 800 mm Brass tube	Re = 1000–4000 (laminar and turbulent flow)	Nu ratio varied from 1.06 to 1.39 when φ increases from 0.5 to 2%
Faulkner et al. [61]	Water	CNT	<100 nm	1.1, 2.2, 4.4	Hydraulic diameter = 355 μm	Re = 2–17 (laminar flow)	HTC was found to be high at higher concentrations
Yang et al. [62]	Oil	Graphite	20–40 nm	0.7–1.0	ID: 4.57 mm Smooth tube	Re = 5 < 110 (laminar flow)	HTC was 22% higher at 50 °C and 15% higher at 70 °C for 2.5 wt%.
Ding et al. [63]	Water	MWCNT	100 nm	0.1–1.0 wt%	ID: 4.5 mm Length: 970 mm Copper tube	Re = 800–1200 (laminar flow)	350% enhancement was found for 0.5 wt% at Re = 800
Yulong et al. [64]	Ethylene glycol	TiO_2 CNT	–	–	–	–	Conv. HTC increases with φ and Re

4.2.1. Inferences from natural convection heat transfer experimental studies

Based on the limited experimental studies and contradictory results found in natural convective heat transfer of nanofluids, a firm conclusion cannot be drawn. However, the heat transfer enhancement of nanofluids in natural convective conditions needs further experimental and theoretical investigations, to exactly predict the behavior of nanofluids. Many factors such as particle size, shape and distribution, and the particle–fluid interactions should also be considered as significant parameters in the heat transfer performance of nanofluids in natural convective heat transfer.

4.3. Boiling heat transfer experiments with nanofluids

Boiling is an effective method of heat removal used in a variety of phase change heat exchanger like boilers, evaporators, etc. When the boiling occurs under a quiescent fluid condition, it is referred to as nucleate boiling and under a forced-flow condition; it is referred as forced convective boiling or convective vaporization. The former depends of the microstructure and the active nucleation cites (pits and crevices, Collier and Thome, [71] of the heat surface and heat flux. Whereas, the latter depend on tube dimension and mass flow rate. The nucleate boiling and its onset depends wall superheat, surface characteristics, presence of dissolved gas, the number of nucleation sites and frequency, and the bubble growth rates. Critical heat flux in pool boiling is peak heat flux under which a boiling surface can sustain nucleate boiling. Reaching the CHF causes a transition from nucleate boiling regime to film boiling regime, which undesirable and causes temperature of the heated surface to reach the melting point. Therefore, an enhanced CHF provides increase in the safety margin of the thermal system and to design compact and efficient cooling systems for electronic devices, nuclear and chemical reactors, air conditioning, etc. Further, the invention of nanofluid has paved way for investigation on improvising the heat transfer in a phase change process. The boiling heat transfer characteristics are broadly investigated with respect to enhancement, critical heat flux and hysteresis. For instance, Chang and You [72] applied micro-porous coat to increase the number of active sites and enhanced the nucleate boiling heat transfer in a plain copper/FC-72 tube by 330% and increased CHF by 100%.

Pool boiling heat transfer using nanofluids has been a subject of many investigations and incoherent results have been reported in literature regarding the same. In the past, experiments were conducted in nucleate pool boiling with varying parameters such as particle size, concentration, surface roughness, etc. and the results showing heat transfer enhancement, deterioration and negligible effect were reported [73,74]. It has been found that deterioration in heat transfer coefficient is mainly observed at higher particle concentrations (4–16% by weight) and enhance-

ments mainly at lower particle concentrations (0.32–1.25% by weight). Moreover, the relative size of the particle with respect to the surface roughness of the heating surface seems to play an important role in understanding the boiling behavior.

Yang and Maa [75] performed pool boiling experiments with Al_2O_3–water (γ = 50, 300 nm, 1 μm) and found that pool boiling performance is greatly improved for φ = 0.1–0.5% in nucleate pool boiling regime. However, micron sized particle suspensions are known to cause problems of erosion and clogging. Das et al. [76] who investigated nucleate pool boiling characteristics of Al_2O_3–water (γ = 20–50 nm; φ = 4–16%) using cartridge heater and found that the nanoparticles sediment on the heater at higher concentration, and deteriorating the boiling performance.

Das et al. [77] showed that pool boiling of nanofluids on narrow horizontal tubes (4 and 6.5 mm diameter. It was found that at this range of narrow tubes the deterioration rate boiling performance with nanofluids is less compared to large industrial tubes, which make it less inclined to local overheating in convective applications because of the relatively small size of the tube.

Bang and Chang [78,79] studied pool-boiling characteristics of Al_2O_3–water nanofluids with (φ = 4–16%) concentration at high heat flux condition. It was observed that the boiling characteristics of nanofluids deteriorated with high concentration similar to Das et al. [76] but the rate of heat transfer was different due to the difference in geometrical features of the heaters in the two studies.

Wen and Ding [80] studied pool boiling heat transfer using spherical Al_2O_3–water (γ = 10–50 nm). The results were quite different from the earlier studies. It was observed that the pure water results matched with the Rohsenow correlation and the heat transfer with nanofluids showed an enhancement in heat flux at the same wall super heat and this enhancement increased with particle volume fraction. It was also observed 40% increase in heat transfer coefficient between nanofluids and pure water. Also, the enhancement was with just 1.25 wt% of particles, which is about 0.3% by volume. Hence, the study concluded saying that this increase is much more than the measured value of thermal conductivity enhancement and hence the boiling enhancement cannot be explained by conductivity enhancement alone.

You et al. [81] performed experiments with alumina-water nanofluids of very small solid particle concentrations (0.0001–0.005% by weight) on a 10 mm square heater in sub-atmospheric conditions and found no significant change in nucleate pool boiling. Vasallo et al. [82] conducted experiments with SiO_2–water nanofluids (γ = 15–50 nm; φ = 2%) on a NiCr wire heater and found no significant change in the boiling performance at low and medium heat fluxes. But at heat fluxes near to CHF of water, it was observed that there is boiling deterioration for the 50 nm nanofluid. Similar increase in CHF is observed in many references (You et al. [81]; Bang and Chang [78,79]; Kim et al. [83,84]; Milanova et al. [85] Jackson et al. [86]).

Witharana [87] carried out experiments using Au–water nanofluids of very low solid particle concentrations (0.001% by weight) on plate heater. An enhancement of 11–21% in heat transfer coefficient was found. With increasing particle concentration the percentage enhancement in heat transfer coefficient also increased.

Nguyen et al. [88] showed enhancement of boiling heat transfer using Al_2O_3–nanofluids (γ = 47 nm) under atmospheric pressure, at various particle concentrations. The critical heat flux had considerably decreased with the augmentation of particle concentrations. For distilled water, the value of CHF was 1192 kW/m^2 which was quite close to that predicted by using the modified Zuber formula. The corresponding values for nanofluids of 0.5, 1 and 2% concentration were 744, 690, and 422 kW/m^2. Thus, the decrease of maximum heat flux was nearly 65% for 2% nanofluid as compared to distilled water.

Jung et al. [89] measured nucleate boiling heat transfer data of eight halocarbon refrigerants and made a specific correlation for halocarbon refrigerants based on the observed data. Test results showed that nucleate boiling HTCs of these halocarbon refrigerants were increased with the addition of CNTs. Especially, heat transfer was enhanced up to 36.6% at low heat flux. As the heat flux increased, the heat transfer enhancement with CNTs decreased. The developed correlation agreed best with these halocarbon refrigerants.

Tu et al. [90] carried out pool boiling experiments using Al_2O_3–water nanofluids on a 26 mm $\times$ 40 mm rectangular surface at the atmospheric pressure and an enhancement of heat transfer of 64% was recorded. Zhou [91] investigated experimentally the heat transfer characteristics of Cu–acetone based nanofluids with and without acoustic cavitation and showed that the copper nanoparticles and acoustic cavitation had significant influence on heat transfer in the fluid. The addition of nanoparticles did not affect the dependence of the heat transfer on acoustic cavitation and fluid sub-cooling. In an acoustic field, the boiling heat transfer of nanofluids was enhanced and the boiling hysteresis disappeared.

Park and Jung [92] conducted a study on nucleate boiling heat transfer coefficients of R123 and R134a, on a 152.0 mm long horizontal plain tube of 19.0 mm outside diameter with and without 1.0 vol.% of carbon nanotubes. The addition of CNTs resulted in heat transfer enhancement at low heat flux was up to 36.6%. Further, unlike conventional nanoparticles, no fouling was observed on the surface with CNTs.

Park and Jung [93] investigated pool boiling of CNT-R22 and CNT–water (φ = 1.0%) of CNTs and showed that CNTs increase boiling heat transfer coefficients of these fluids up to 28.7%. With increasing heat flux, however, the enhancement was suppressed due to vigorous bubble generation. Penetration into the thermal boundary layer by CNTs to generate more bubbles at the surface seemed to be the key element in the improvement of nucleate boiling heat transfer associated with the use of CNTs.

4.3.1. *Inferences from boiling heat transfer experimental studies*

The observations based on the studies of boiling heat transfer of nanofluids shows that the boiling performance is inversely proportional to nanoparticle concentration. However, Wen and Ding [80] have reported a trend contradictory to this. As far as the effect of nanoparticles on the boiling heat transfer performance is concerned, conflicting results were observed from these limited data. The inconsistencies indicate that the understanding of the thermal behavior of nanofluids related to the boiling heat transfer is still poor. The pool boiling is affected by the surface properties such as surface roughness, surface wettability, and surface contamination. In the reviewed studies, only the surface roughness is the most often considered parameter. Also no study on boiling of metallic nanofluids or flow boiling of nanofluids is available. Further, detailed investigations are necessary to understand the phenomena of boiling of nanofluids and the influence on the above factors.

5. Mathematical modeling

5.1. *Theoretical investigations for convective heat transfer of nanofluids*

The mixture of nanoparticles and base fluid is a multiphase problem and thus, could be approximated as either a homogeneous fluid or heterogeneous mixture. In the case of a homogeneous approach, because of the size of the nanoparticles, it has been suggested that these particles may easily be fluidized and consequently, can be considered to behave more like a single phase fluid. Further, by assuming a negligible motion slip between

the particles and the thermal equilibrium conditions, the nanofluid could be considered as a conventional single-phase fluid with averaged physical properties of individual phases [39,94]. However, because the effective properties of the nanofluids are not known precisely, the numerical predictions of this approach are not in good agreement with the experimental results. Choi et al. [95] first adopted a homogeneous model and used the conventional heat transport equations for pure fluids, such as the Dittus–Boelter correlation, to the nanofluids. In the case of a heterogeneous approach (two-phase), factors such as gravity, friction between the phases, Brownian diffusion, sedimentation, and dispersion are included in the flow model. The two-phase approach provides the possibility of understanding the functions of both the fluid phase and the solid particles in the heat transfer process, and provides a field description of both the phases.

Xuan and Roetzel [96] proposed a two-phase thermal dispersion model and assumed that the convective heat transfer enhancement in nanofluids comes from two factors, (i) higher thermal conductivity, and (ii) the thermal dispersion of the nanoparticles. In this approach, the effect of the nanoparticle/base fluid relative velocity and temperature are treated as a perturbation of the energy equation. The thermal dispersion coefficient was introduced to describe the heat transfer enhancement. Khanafer et al. [97] investigated the heat transfer enhancement in a two-dimensional enclosure utilizing the nanofluid. The effective thermal conductivity was taken as the sum of the mixture thermal conductivity evaluated from the conventional theory and a dispersion thermal conductivity. It was observed that in any of the numerical studies in convection, the effect of temperature on thermal conductivity was not considered. However, the effect of temperature on the thermal conductivity of nanofluids was proved significant from studies made by Das et al. [98].

Buongiorno [99] developed an alternative model that eliminates the shortcomings of the homogeneous and dispersion models. The homogeneous flow models are in conflict with the experimental observation and the pure-fluid correlations underpredict the heat transfer coefficient. In this model, a detailed analysis of convective transport with seven slip conditions between particles and fluid were considered, for explaining the enhancement of heat transfer with nanofluids. In these mechanisms the Brownian diffusion and thermophoresis were the two most important nanoparticles/base fluid slip mechanisms. Convective heat transfer enhancement was obtained with a decrease in viscosity and consequent thinning of the laminar sub-layer. It was observed that the radial distribution of the particle concentration (more concentration at the core than the walls) brought about by thermophoresis make the temperature profile flatten, thus giving a higher heat transfer coefficient and finally, a new correlation was developed to predict the enhanced heat transfer coefficient of nanofluids.

Behzadmehr et al. [100] applied a two-phase mixture model to study the heat transfer of nanofluids (Cu–water; $\varphi = 1\%$) for forced turbulent convection in a uniformly heated tube. The Nusselt number increased by more than 15%, was proportional to the Reynolds number and resulted in a more uniform velocity profile. The frictional coefficient decreased as the Reynolds number increased when compared with that of pure fluid. Finally, increasing particle concentration caused the Nusselt number to increase and thus, the convective heat transfer coefficient.

Maïga et al. [101] modeled the forced convection flow of a nanofluid (γAl_2O_3 with water and ethylene glycol) in a straight tube of circular cross-section. A single-phase flow was assumed to derive the governing equations to calculate the heat transfer enhancement by the nanofluids in the laminar flow as well as the turbulent flow regime, with nanofluid concentrations ranging from 0 to 10%. For laminar flow, the results indicated an increase in the heat transfer rate, particularly at the walls, with the augmentation of φ (for $\varphi = 10\%$, the product ρc_p and thermal conductivity, k increased by ~18 and ~33%, respectively). The heat transfer coefficient ratio h_r also increases with particle loading and particularly at the tube end (by nearly 60%). Further, averaged heat transfer enhancement was clearly more pronounced for the γAl_2O_3–ethylene glycol than for the γAl_2O_3–water nanofluid for $\varphi > 3\%$ (identical otherwise). The wall shear stress was found to increase considerably with the particle volume fraction and along the tube length. For the turbulent flow regime, the heat transfer coefficient increased steeply for a very short distance from the inlet section. The properties h_r and τ_r varied in a similar manner as in the previous case.

Roy et al. [102] modeled the hydrodynamic and thermal fields of a γAl_2O_3–water nanofluid ($\varphi = 1$–10%) in a radial laminar flow cooling system. Considerable increases in the wall shear stress were predicted on account of the increase in the fluid viscosity (a maximum of 2.5-fold increase for $\varphi = 5\%$). Overall, the study indicated that considerable heat transfer enhancement was possible and a maximum increase of twice the value of the base fluid in the case of $\varphi = 10\%$. Ding and Wen [103] modeled the effects of particle migration in pressure driven laminar flows of nanofluids and predicted the particle concentration and velocity field of nanofluids; in the transverse plane of the pipe by taking into account the effects of the shear induced and viscosity gradient induced particle vibrations as well as self-diffusion due to the Brownian motion. Two approaches were used, one was based on mass conservation law for the dispersed phase and the other on the momentum balance of the particle phase. The results indicate that the Peclet number increased rapidly with increasing particle size and Reynolds number. The Brownian motion had a significant effect on the particle migration of nanofluids and became important at Peclet numbers less than 10. At the limit of zero Peclet number, the particle concentration is uniform. Further, the smaller the particle size, the more uniform the distribution of particles in the transverse plane. The existence of an optimal particle size at which the thermal conductivity was enhanced with little penalty due to pressure drop is suggested.

Palm et al. [104] numerically investigated the enhanced heat transfer capabilities of Al_2O_3–water ($\gamma = 38$ nm; $\varphi = 1$–4%) in a radial laminar flow cooling system and used temperature-dependant nanofluid properties. The experimental results obtained using the single-phase approach indicated that property fluctuations are noticed near the injection inlet. Lower viscosities at higher temperature, decrease in wall shear stress for increase in wall heat flux and greater wall heat transfer rates were shown when compared to predictions using constant properties.

Kim et al. [105] theoretically investigated the Thermo-diffusion (Soret effect) and diffusion thermo (Dufour effect) effects on convective instabilities in binary nanofluids (the base-fluid is a binary mixture). Data from silver and copper nanofluids studies were used in this investigation, which showed that the particles caused a unique convective motion in binary nanofluids. The heat transfer enhancement by the Soret effect in binary nanofluids is more significant than that in mono-nanofluids. Further, the heat transfer coefficient of silver nanofluids was higher than that of copper, owing to the higher thermal conductivity of silver. Studies predicted that the Soret and Dufour diffusions make the nanofluids unstable and this was more profound for denser nanofluids. Further, the convective motion in nanofluids sets easily in both the effects as the concentration increased.

Mansour et al. [106] investigated the effect of the Hamilton–Crosser model and the Modified Maxwell model, to predict nanofluid (γAl_2O_3–water; $\varphi = 1$–10%) physical properties, on their thermal and hydrodynamic performance for both fully developed laminar and turbulent forced convection in a tube with uniform

Table 2
Existing convective heat transfer correlations for nanofluids.

Reference	Correlation
Pak and Cho [39]	$\mathrm{Nu} = 0.021\,\mathrm{Re}^{0\ 8}\mathrm{Pr}^{0.5}$
Xuan and Li [57]	$\mathrm{Nu} = 0.4328(1.0 + 11.285\varphi^{0.754}\mathrm{Pe}_{\mathrm{p}}^{0.218})\mathrm{Re}_{\mathrm{nf}}^{0.333}\mathrm{Pr}_{\mathrm{nf}}^{0.4}$ for laminar flow $\mathrm{Nu} = 0.0059(1.0 + 7.6286\varphi^{0.6886}\mathrm{Pe}_{\mathrm{p}}^{0.001})\mathrm{Re}_{\mathrm{nf}}^{0.9238}$ for turbulent flow
Maiga et al. [65]	$\mathrm{Nu} = 0.86\,\mathrm{Re}^{0\ 55}\mathrm{Pr}^{0.5}$ for constant wall heat flux $\mathrm{Nu} = 0.86\,\mathrm{Re}^{0.35}\mathrm{Pr}^{0.36}$ for constant temperature
Buongiorno [40,99]	$\mathrm{Nu}_{\mathrm{b}} = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+\delta_v^{+}\sqrt{(f/8)}(\mathrm{Pr}_v^{2/3}-1)}$
Maïga et al. [118]	$\mathrm{Nu} = 0.085\,\mathrm{Re}^{0\ 71}\mathrm{Pr}^{0.35}$ for fully developed (fd) turbulent flow

heat flux at the wall. Two models gave substantially different results for thermal conductivity, specific heat and viscosity, and the differences were more profound for higher particle loading. The expressions failed to account for the size disparity between the nanoparticles. The two models revealed in very different predictions and it was not possible to ascertain which was accurate. The study illustrated that the operational conditions or the design parameters varied significantly with the thermo-physical properties of the nanofluid.

Prakash and Giannelis [107] calculated the thermal conductivity of nanofluids (Al_2O_3–water and ethylene glycol) using temperature and concentration dependent viscosity relations. The temperature profile was obtained using the Gaussian fit to the available experimental data. The micro-convection of the alumina nanoparticle ($\gamma < 100$ nm) was included through the Reynolds and Prandtl numbers. The model was further improved by explicitly incorporating the thermal conductivity of the nano-layer surrounding the nanoparticles. The results indicated that the thermal conductivity ratio depends on both the temperature variation in viscosity and the Brownian motion. However, the thermal conductivity was more sensitive to the Reynolds number than to the Prandtl number. As a result, there is net enhancement in thermal conductivity as the temperature was increased. Studies showed that a cylindrical-shaped particle leads to much higher thermal transport than a spherical-shaped particle.

Li and Peterson [108] simulated the mixing effect of the base fluid with nanoparticles caused by the Brownian motion; they modeled and compared it with the existing experimental data available in the literature. The mixing effect predicted a significant influence on the effective thermal conductivity of nanofluids.

5.2. Inferences from theoretical studies with nanofluids

The observations based on the reviewed literature for theoretical studies in the convective heat transfer of nanofluids clearly shows, that the models developed by the various researchers have been satisfactory only under very stringent conditions. However, a generalized theoretical model should be developed by considering all the factors such as inertia, thermophoresis, Brownion motion, and gravity which influences the heat transfer characteristics and the behavior of nanofluids under convective heat transfer conditions. The correlations based on the experimental data for finding the Nusselt number of nanofluids

Table 3
Summary of theoretical investigations in convective heat transfer of nanofluids.

Author	Theoretical investigations	Approach	Results and remarks
Xuan and Li [28]	Theoretical heat transfer characteristics of transformer oil–Cu and water–Cu nanofluids	Single phase fluid approach	The heat transfer coefficient improved dramatically with decrease in particle size and not only due to thermal conductivity increase
Xuan and Roetzel [96]	Heat transfer of nanofluids	1. Single phase fluid approach 2. Dispersion model approach	Suspended particles increase the thermal conductivity. Chaotic movement of ultrafine particles and the thermal dispersion accelerates the energy exchange process
Buongiorno [40,99]	Convective transport in nanofluids	Two-component non-homogeneous equilibrium model	Brownian diffusion and thermophoresis are the two most important nanoparticles/basefluid slip mechanisms
Behzadmehr et al. [100]	Turbulent forced convection flow in a uniformly heated tube	Two phase mixture model	HTC increases with φ and Re. Higher Re resulted more uniform velocity profile
Maiga et al. [101]	Forced convection flow of nanofluid (water/Al_2O_3 and ethylene glycol/Al_2O_3) in a circular tube	Single phase fluid approach	60% enhancement in HTC was found and turbulent flow enhancement increases with Re
Roy et al. [102]	Hydrodynamic and thermal flow fields of water/Al_2O_3 nanofluid in a radial laminar flow cooling system		Two fold increase in heat transfer coefficient was observed along with wall shear stress and particle concentration
Ding and Wen [103]	Effects of particle migration in laminar flows of nanofluids	Mass conservation laws and momentum balance	Shear induced migration, viscosity gradient migration and self-diffusion. Highly non-uniform thermal conductivity profile obtained
Palm et al. [104]	Heat transfer capabilities and temperature-dependant properties of nanofluids in radial flow cooling systems	Single phase fluid approach	Temperature dependent properties lead to greater heat transfer performance with the decrease in wall shear stresses
Kim et al. [105]	Thermo diffusion (Soret effect), diffusion thermo (Dufour effect) effects in binary nanofluids	One fluid model	As the Soret and Dufour effects and φ increases the convective motion sets in easily
Mansour et al. [106]	Thermal and hydrodynamic performance for both laminar and turbulent forced convection in a tube with uniform heat flux at the wall	Single phase fluid approach	Both the models predicted increased HTC with particle concentration
Prakash and Giannelis [107]	Thermal conductivity of Al_2O_3 nanofluids using temperature and concentration dependent viscosity		Dependence of the thermal conductivity on the size of the nanoparticle, temperature viscosity and particle concentration
Maïga et al. [118]	Forced convection flow of nanofluid (water/Al_2O_3 and ethylene glycol/Al_2O_3) in a circular tube and radial channel between a pair of parallel coaxial discs	Single phase fluid approach	HTC increased by 63 and 45%. Increased heat transfer and dynamic viscosity resulted in increased wall shear stress with partial loading

from laminar to turbulent regions reported in the published literature are presented in Tables 2 and 3 gives a summary of the various theoretical investigations in the convective heat transfer of nanofluids.

6. Applications

6.1. Micro-channels

The micro-channel heat sink (MCHS) has the capability to dissipate large amounts of heat from a small area with a very high heat transfer coefficient and less fluid inventory. Using nanofluids as a coolant in the MCHS could further improve its performance. Chein and Huang [109] analyzed the performance of the MCHS (silicon channel of $100\,\mu m \times 300\,\mu m$ dimension) using a Cu–water nanofluid with $\varphi = 0.3$–2%. The Nusselt number increased significantly with an increase in Re and φ. The maximum reduction in thermal resistance as compared to pure water was found to be 15% at $\varphi = 2\%$ and power = 3 W. The additional reduction in R_{th} is clearly due to thermal dispersion. With regard to pressure drop, no significant differences existed between the nanofluid and water flows.

Jang and Choi [110] numerically investigated the cooling performance of a silicon micro-channel heat sink under forced convective flow with nanofluid (Cu–water; $\gamma = 6$ nm and diamond–water; $\gamma = 2$ nm particle size) for $\varphi = 1\%$. The nanofluids reduced the thermal resistance of the heat sink and enhanced the cooling performance by 10 and 4%, respectively. Further, the potential of employing a micro-channel heat sink with nanofluid to remove ultra high heat flux as much as 1350 W/cm^2 when the difference between the junction temperature and inlet coolant temperature is 80°C, was demonstrated.

Chein and Chuang [111] used a nanofluid (CuO–water, $\varphi = 0.204$, 0.256, 0.294 and 0.4%) with 80 nm long and 20 nm wide particles. The energy absorbed by the nanofluid was greater than that absorbed by water and was found to increase with the increase in particle volume fraction. A large temperature difference between the MCHS inlet and outlet was obtained at a low flow rate. Thermal resistance was found to reduce with an increase in the flow rate. Although the nanofluids had higher viscosity, only a marginal increase (around 5%) in the pressure drop across the MCHS was reported.

Koo and Kleinstreuer [112] simulated and analyzed the conduction-convection heat transfer of nanofluid (CuO–water and ethylene glycol, $\gamma = 20$ nm) in a micro-channel ($300\,\mu m \times 50\,\mu m$). The new model incorporated static and Brownian heat transfer, and hence the thermal conductivity and dynamic viscosity were suggested to be $k_{eff} = k_{static} + k_{Brownian}$ and $\mu_{eff} = \mu_{static} + \mu_{Brownian}$. The Nusselt number for ethylene glycol based nanofluids was always higher than for water based ones, due to stronger thermal flow development effects. Moreover, the viscous dissipation effect was found to affect only ethylene glycol based nanofluids and was more important for flows through very narrow channels.

Nguyen et al. [113] investigated the heat transfer enhancement of Al_2O_3–water ($\gamma = 36$ and 47 nm) in the cooling systems of microprocessors and electronic components. The inclusion of nanoparticles in distilled water produced a considerable enhancement convective heat transfer coefficient (around 40% for $\varphi = 6.8\%$) and a clear decrease of the heated component temperature was recorded. In addition, smaller nanoparticles were found to produce greater enhancement in the heat transfer coefficient.

6.2. Heat pipes

Chien et al. [114] studied heat transfer in a disk-shaped miniature heat pipe (DMHP) using nanofluid (Au–DI water; $\varphi = 18$, 37 and 55%; $\gamma = 17$ nm). The average decrease of 40% in thermal resistance was achieved as compared to that of pure DI water. Tsai et al. [115] studied a heat pipe using the Au–DI water nanofluid ($\gamma = 8$–43.7 nm) and a 37% lower thermal resistance was achieved (at $\gamma = 21.3$ nm) when compared to that of DI–water. Smaller nanoparticles have greater reduction in thermal resistance in conditions of equal aggregation. A major reduction in thermal resistance is from the evaporator section to the adiabatic section (a maximum of 56% reduction), which is attributed to the bombardment of vapor bubbles by the nanoparticles.

Kang et al. [116] investigated heat transfer in a grooved heat pipe using Ag–water and Ag–DI water ($\gamma = 10$–35 nm) with particle concentrations ranging from 1 to 100 mg/l. The results indicated that after adding a small amount of silver nanoparticles in pure water, the heat pipe wall temperature became lower than that of pipes filled only with pure water. As more nanoparticles became dispersed in the working fluid, the heat pipe wall temperature increase became smaller. The maximum reduction in thermal resistance of a heat pipe containing $\gamma = 10$ nm was 52% lower, while that containing $\gamma = 35$ nm was 81% lower than that of DI–water. The enhancement of heat pipe performance was attributed to the increase in effective liquid conductance that flattens the temperature of the fluid.

Ma et al. [117] studied the nanofluid (diamond–water; $\varphi = 1\%$) behavior in an oscillating heat pipe (OHP) and thus developed an ultrahigh performance cooling device, called the nanofluid oscillating heat pipe in which when the input power was increased to the highest value, the temperature difference between the evaporator and the condenser for the nanofluid OHP was less than that for the OHP with only pure water.

7. Outlook and future challenges

Many interesting properties of nanofluids have been reported in the review. In the previous studies, thermal conductivity has received the maximum attention, but many researchers have recently initiated studies on other heat transfer properties. The use of nanofluids in a wide variety of applications appears promising. But the development of the field is hindered by (i) lack of agreement of results obtained by different researchers; (ii) poor characterization of suspensions; (iii) lack of theoretical understanding of the mechanisms responsible for changes in properties. Therefore, this article concludes by outlining several important issues that should receive greater attention in the near future. Experimental studies in the convective heat transfer of nanofluids are needed. Many issues, such as thermal conductivity, the Brownian motion of particles, particle migration, and thermophysical property change with temperature, must be carefully considered with convective heat transfer in nanofluids. Though, all the convective studies have been performed with oxide particles in high concentrations, (for example Pak and Cho [39] used 10 vol.% of Al2O3 which increased the viscosity and pumping power of the fluid), it is interesting to know the energy transport in low-concentration (<1 vol.%) nanofluids with metallic particles, since the thermal conductivity of pure metallic nanoparticles is more than 100 times higher than that of the oxide nanoparticles. Future convective studies must be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulence regions. The use of nanofluids in heat pipes has shown enhancement in performance and considerable reduction in thermal resistance. However, recent studies indicate particle aggregation and deposition in micro-channel heat sinks. Further study is required in these areas to identify the reasons for and the effects of particle deposition. Finally, there appears to be hardly any research in the use of nanofluids as refrigerants. Nanoparticle-refrigerant dispersions in two-phase heat transfer applications can be studied

to explore the possibility of improving the heat transfer characteristics of evaporators and condensers used in refrigeration and air-conditioning appliances. Applied research in nanofluids which will define their future in the field of heat transfer is expected to grow at a faster pace in the near future.

8. Conclusion

The present review is a comprehensive outlook on the research progress made in the convective heat transfer characteristics of nanofluids. The salient feature that can be drawn from the reviewed literature is that nanofluids are a new class of heat transfer fluids and show greater promise for use in cooling and related technologies. From the observed results it is clearly seen, that nanofluids have greater potential for heat transfer enhancement and are highly suited to application in practical heat transfer processes. This offers an opportunity for engineers to develop highly compact and effective heat transfer equipment. Several published articles show that the heat transfer coefficient of nanofluids is much higher than that of the common-base fluid and gives little or no penalty in pressure drop. The main reason for the heat transfer enhancement of nanofluids is that the suspended nanoparticles increase the thermal conductivity of the fluids, and the chaotic movement of ultrafine particles increases fluctuation and turbulence of the fluids, which accelerates the energy exchange process. Convective heat transfer is enhanced by increasing the particle concentration and the Reynolds number. Besides, the experimental data available for convective heat transfer in laminar, transition and turbulence regions are limited and insufficient to exactly predict the trend for heat transfer enhancement. Furthermore, only very few correlations are available to exactly predict the heat transfer performance of nanofluids, and correlations which include the effect of volume fraction, particle shape and particle size are nil to-date. Therefore, further research on convective heat transfer of nanofluids, and more theoretical and experimental research works are needed in order to clearly understand and accurately predict their hydrodynamic and thermal characteristics. The trends reported in literature on nucleate boiling of nanofluids are conflicting and the results are contradicting. The authors have tried to arrive at a common reasoning for the seemingly conflicting results. Also no study on boiling of metallic nanofluids or flow boiling of nanofluids is available. Further work is required to determine the effect of surface wettability on pool boiling of nanofluids in the nucleate boiling regime especially for the low concentration metallic nanoparticles.

Generally, many researchers indicated that nanofluids behave like pure fluids because the suspended particles are ultrafine. However, at present, no formulated advanced theory exists to explain the behavior of nanofluids by considering them as multi-component materials. Greater enhancement was observed when nanofluids were used in heat pipes and in micro-channel heat sinks, as well as other applications. Further, theoretical and experimental research investigations are needed to comprehensively understand the heat transfer mechanism in nanofluids for evolving new energy efficient heat transfer fluids specific to applications.

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